Selection of the longitudinal elevation and gradients

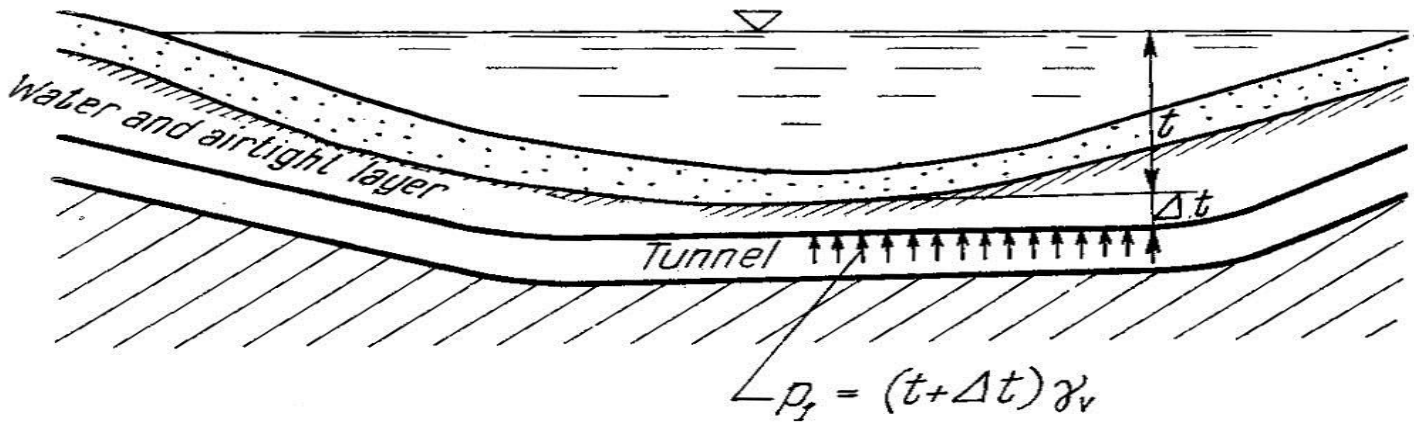
Ruling grade

- The elevation at which the tunnel is located is equally significant for both construction and traction,

- the layer in which the tunnel will be driven and its position relative to the ground water table, and grade being dependent on this decision.

- For tunnels in mountains the aspect of traction and operation, and sometimes the position of ground water, may be the primary factors in the selection of elevation,
- The depth of underwater tunnels is controlled primarily by geological conditions. Grade, traction and operation must be subordinated and adjusted accordingly.

  Accurate information must be obtained first of all on the bed contours on the elevation and succession of soil layers and particularly on the depth (t) and thickness (Δ t) of the impervious layer (cover). The tunnel must be located in the impervious layer under an adequately thick cover, with a thickness sufficient to prevent the inrush of water.



Ruling grade

The **ruling grade** is the steepest gradient on a line where the gradient varies. It has an allowable maximum value according to the power, weight, traction and resistance of the train, which will be using the tunnel.

As far as traction is concerned, the ruling grade permissible in tunnels is smaller than in the open air, owing to the reduced adhesion and increased air resistance in tunnels. *The first reduction factor is the decrease in the traction force due to the adhesion-coefficient in tunnels.*

For railroads, resistances are the following:

- *Due to friction of the wheel bearings*
- *Parasite movements of railroad cars such as forward and lateral cause energy losses*
- *Dynamic blows cause shape changes in both rails and wheels*
- *Rolling resistance*
- *Moving railroad cars cause air friction. Air resistance is different in open air and in the tunnel and changes with the wind direction.*
- *Grade resistance develops on sloped section of the profile*
- *Curve resistance*

Therefore the total resistance to movement can be summarized as:

W = Wo + Ws + Wt + Wr

- **Wo** = Open air (0 grade) resistance (kg/ton)
- **Ws** = Grade resistance (kg/ton)
- **Wt** = Tunnel resistance (kg/ton)
- **Wr** = Resistance due to curves (kg/ton)

Wo is composed of

Wo = Wo1+ Wo2 + Wo3+ Wo4

- **Wo1** ; Axle resistance due to friction
- **Wo2** ; Rolling resistance
- **Wo3** ; Resistance developed at the chassis and shock absorbers, they are negligible as they are very small
- **Wo4**; Air resistance composed of locomotive, car, and train side resistances

The atmosphere in tunnels is usually saturated with moisture, owing to the vapour, which precipitates from warm air in summer, and to ground water infiltration. Moisture precipitated this way causes a significant reduction of the adhesion-coefficient between wheels and rails.

The degree of adhesion is affected by several other factors as well, such as the elevation of the tunnel above sea level, the situation of the tunnel portals, wind and sunshine conditions, the cross-sectional dimensions of the tunnel, ventilation and draught, etc. Consequently the traction force of the locomotive will drop from the open-air value

$$V = 1000\, f\, Q_a$$

to

$$V_1 = 1000\, f_1 Q_a$$

Where; Q_a is the adhesive weight of the locomotive

The ruling grade is naturally also affected thereby, since in the case of constant motion the tractive force must equal the sum of resistances, or, on an open-air line

$$1000\, f_1 Q_a = Q(\mu + e_m)$$

Where; Q = the weight of the train

μ = its specific resistance

e_m = the ruling grade per mile

The weight Q of the train to be handled remains the same in the tunnel, neither does the value of μ change, so that the ruling grade e_m must decrease to e_1 in order that the reduced tractive force V_1 should not lead to deceleration, since

$$1000\ f_1 Q_a = Q(\mu + e_1)$$

by division of one equation by the other we obtain

$$\frac{f}{f_1} = \frac{\mu + e_m}{\mu + e_1}$$

where;

$$e_1 = \frac{f_1}{f}\,\mathrm{e}_{\mathrm{m}} - \mu\left(1 - \frac{f_1}{f}\right)$$

- Assuming the conventional value of **3-3.5 kg/ton for μ** (slow, heavy freight trains with v = 30 to 55 km/h are decisive in this respect), the value of e_1 can be computed in terms of em. As will be perceived the reduction is appreciable and depends, naturally, on the absolute value of the ruling grade as well.

- In the case of electric traction e_1 may be assumed a value range of 2.0-2.5%.

- Besides the reduction in the traction force the increase in air resistance is also a factor necessitating a reduction in the ruling grade. Denoting this share of the ruling grade by Δe, we obtain the previous equation in the following complete form:

$$e_1 = \frac{f_1}{f}\,\mathrm{e}_{\mathrm{m}} - \left[\Delta e + \mu\left(1 - \frac{f_1}{f}\right)\right]$$

The ***magnitude of air resistance*** is known to depend on the relative velocities of wind and train, greater resistance upwind than downwind, as wells as on the relative cross-section areas of tunnel and train.

The *magnitude of the resistance* and the factors involved have been obtained *experimentally* by measurements in wind tunnels and existing tunnels.

Resistance is especially large in single track tunnels which are comparatively narrow. The train proceeds in a relatively restricted space and is preceded by a compression wave and followed by a depression wave.

The first experimental measurement on the increase of air resistance was carried out in the Simplon tunnel, which consists of two single track tunnels spaces at 12 m provided with artificial ventilation. Air resistance was measured first on the open line, then in the tunnel in the direction or the air stream and subsequently against a forced draught. The train proceeded at different speeds. The results of these measurements are compiled in the table on page 30.

Air resistance measurements were performed in the tunnels of the London Underground Railway. The parameters included

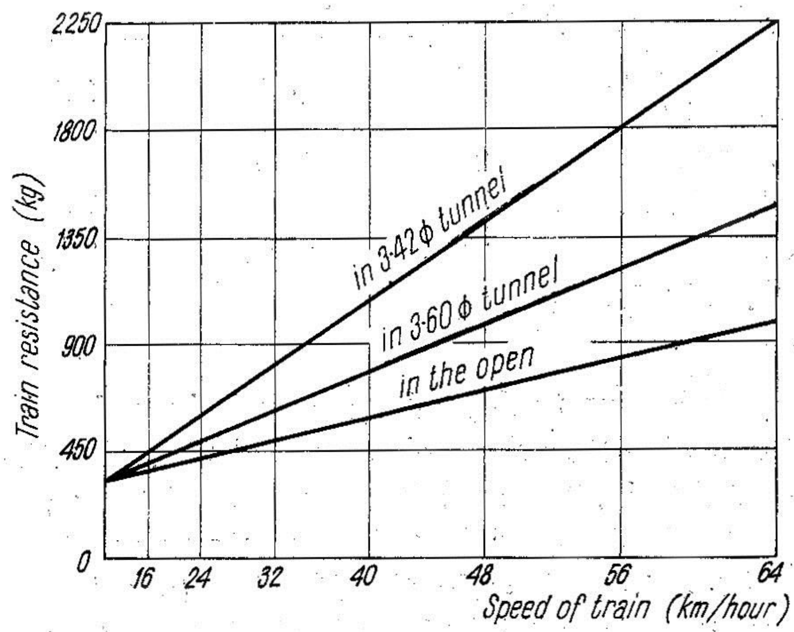
- the velocity of the train,
- the ratio between the tunnel cross-section,
- the front area of the train, and
- the internal roughness.

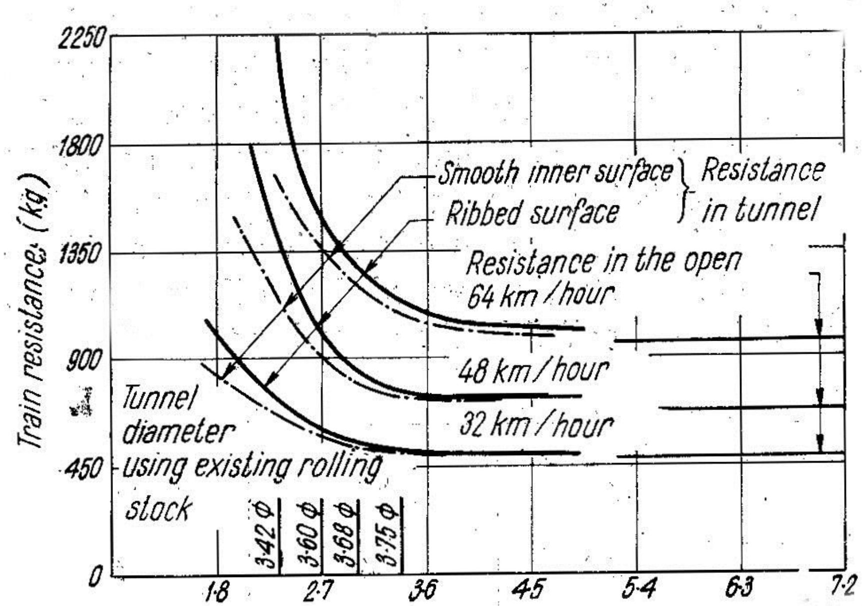
The results are represented graphically in the figures. As can be seen from the figures

The measured resistance increased in a practically linear ratio with the speed, ***but the gradient of the straight line was a function of the tunnel diameter***. ***Beyond a certain limit this influence appeared to decrease appreciably.***

The differences between the cross-section area of the tunnel and the front area of the train (i.e. the free area ∆ F) are indicated here on the abscissa and the magnitude of the resistance on the ordinate axis.

Values pertaining to different speeds are connected by corresponding curves. ***As indicated by the trend of these curves, the effect on the free cross-section area becomes negligible as soon as the value of ∆ F reaches 4-5 m², i.e. about 40% of the total cross-section area.*** The influence of the ribbed tube lining becomes entirely negligible at the same limit, but it was found to be altogether appreciable smaller than that of the previous factors.





- The reduction of grade due to the increased resistance should be started at a distance corresponding to ***one half of the train length*** before the adit, rather than at the portal itself.
- Grade conditions within the tunnel are influenced to a certain extent also by ***considerations of drainage***; proper drainage must be ensured in every tunnel. The minimum slope required for this reason is 0,2% but 0,3% is preferable. Tunnels are usually made to slope in two directions outward from a central apex in the mountain. If the tunnel is not at the highest elevation of the line and is on a gradient, or is not too long, a unidirectional slope may be used. Outward slopes towards the portals have the advantage or ready drainage away from the driving faces at both ends. In the case of a unidirectional slope, on the other hand, the water must be pumped from the heading starting at the upper end. The water from underwater tunnels should be drained to collection sumps constructed under the adit or ventilation shafts at the banks, where is must be removed by continuous pumping. Drainage by gravity can be affected only in tunnels elevated above the ground-surface.